SIVERS AND COLLINS SINGLE SPIN ASYMMETRIES

A. V. Efremov[1†], K. Goeke[2] and P. Schweitzer[2]

(1) *Joint Institute for Nuclear Research, Dubna, 141980 Russia*
(2) *Institut für Theoretische Physik II, Ruhr-Universität Bochum, Germany*
† *E-mail: efremov@theor.jinr.ru*

Abstract

The Sivers and Collins asymmetries are the most prominent Single Spin Asymmetries (SSA) in Semi-Inclusive Deeply Inelastic Scattering (SIDIS) with transverse target polarization. In this talk we present our understanding of these phenomena.

1 Introduction

SSAs in hard reactions have a long history dating back to the 1970s when significant polarizations of Λ-hyperons in collisions of unpolarized hadrons were observed [1], and to the early 1990s when large asymmetries in $p^{\uparrow}p \to \pi X$ or $p^{\uparrow}\bar{p} \to \pi X$ were found at Protvino [2] and FNAL [3]. No fully consistent and satisfactory unifying approach to the theoretical description of these observations has been found so far — see the review [4].

Interestingly, the most recently observed SSA and azimuthal phenomena, namely those in SIDIS and e^+e^- annihilations seem better under control. This is in particular the case for the transverse target SSA observed at HERMES and COMPASS [5, 6, 7] and the azimuthal correlations in hadron production in e^+e^- annihilations observed at BELLE [8]. On the basis of a generalized factorization approach in which transverse parton momenta are taken into account [9] these "leading twist" asymmetries can be explained [10, 11] in terms of the Sivers [12, 13, 14, 15] or Collins effect [16]. The former describes, loosely speaking, the distribution of unpolarized partons in a transversely polarized proton, the latter describes a left-right asymmetry in fragmentation of transversely polarized partons into unpolarized hadrons. In the transverse target SSA these effects can be distinguished by the different azimuthal angle distribution of the produced hadrons: Sivers effect $\propto \sin(\phi - \phi_S)$, while Collins effect $\propto \sin(\phi + \phi_S)$, where ϕ and ϕ_S denote respectively the azimuthal angles of the produced hadron and the target polarization vector with respect to the axis defined by the hard virtual photon [10]. Both effects have been subject to intensive phenomenological studies in hadron-hadron-collisions [17] and in SIDIS [18]-[26]. In this talk our understanding of these phenomena is presented.

For the longitudinal target SSA in SIDIS, which were observed first [27, 28] but are dominated by subleading-twist effects [29, 30], the situation is less clear and their description (*presuming* factorization holds) is more involved.

2 Sivers effect

The Sivers effect [12] was originally suggested to explain the large SSAs in $p^{\uparrow}p \to \pi X$ (and $\bar{p}^{\uparrow}p \to \pi X$) observed at FNAL [3] and confirmed at higher energies by RHIC [31]. It is due a correlation between (the transverse component of) the nucleon spin $\mathbf{S}_{\rm T}$ and intrinsic transverse parton momenta $\mathbf{p}_{\rm T}$ in the nucleon, and decribed by the Sivers function $f_{1T}^{\perp}(x, \mathbf{p}_T^2)$ whose precise definition in QCD was worked out only recently [14, 15].

2.1 Sivers effect in SIDIS. The azimuthal SSA measured by HERMES & COMPASS in the SIDIS process $lp^\uparrow \to l'hX$ (see Fig. 1) is defined as

$$\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \propto \underbrace{\sin(\phi - \phi_S)\, A_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers}} + \underbrace{\sin(\phi + \phi_S)\, A_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins effect}} \qquad (1)$$

and

where $N^{\uparrow(\downarrow)}$ are the event counts for the respective transverse target polarization. We assume the distributions of transverse parton and hadron momenta in distribution (DF) and fragmentation function (FF) to be Gaussian with corresponding averaged transverse momenta, $p^2_{\rm Siv}$ and $K^2_{D_1}$, taken x- or z- and flavour-independent. The Sivers SSA as measured in [5, 6] is then given by [21]

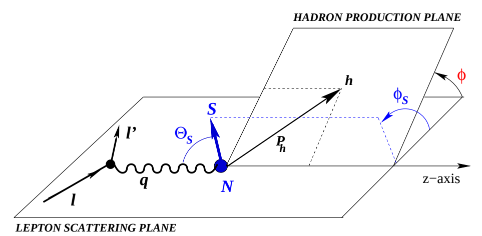

Figure 1: Kinematics of the SIDIS process $lN \to l'hX$.

$$A_{UT}^{\sin(\phi-\phi_S)} = (-2)\, \frac{a_{\rm G} \sum_a e_a^2\, x f_{1T}^{\perp(1)a}(x)\, D_1^a(z)}{\sum_a e_a^2\, x f_1^a(x)\, D_1^a(z)} \quad \text{with} \quad a_{\rm G} = \frac{\sqrt{\pi}}{2} \frac{M_N}{\sqrt{p^2_{\rm Siv} + K^2_{D_1}/z^2}} \qquad (2)$$

and $f_{1T}^{\perp(1)a}(x) \equiv \int {\rm d}^2\mathbf{p}_T \frac{\mathbf{p}_T^2}{2M_N^2} f_{1T}^{\perp a}(x, \mathbf{p}_T^2)$. In the limit a large number of colours N_c one has

$$f_{1T}^{\perp u}(x, \mathbf{p}_T^2) = -f_{1T}^{\perp d}(x, \mathbf{p}_T^2) \quad \text{modulo } 1/N_c \text{ corrections,} \qquad (3)$$

and analog for antiquarks for x of the order $xN_c = \mathcal{O}(N_c^0)$ [32]. In the following effects of antiquarks and heavier flavours are neglected. It was shown [21] that the large-N_c relation (3) describes the HERMES data [5] by the following 2-parameter Ansatz and best fit

$$x f_{1T\,{\rm SIDIS}}^{\perp(1)u}(x) = -x f_{1T\,{\rm SIDIS}}^{\perp(1)d}(x) \overset{\rm Ansatz}{=} A\, x^b\, (1-x)^5 \overset{\rm fit}{=} -0.17 x^{0.66} (1-x)^5 \,. \qquad (4)$$

Fig. 2a shows the fit and its 1-σ uncertainty due to the statistical error of the data [5]. Fig. 2b shows that this fit very well describes the x-dependence of the HERMES data [5]. Fig. 2c finally shows the equally good description of the z-dependence of the data [5] that were not included in the fit, and serves here as a cross check for the Gauss Ansatz.

We have explicitly checked that effects due to Sivers $\bar u$- and $\bar d$-distributions cannot be resolved within the error bars of the data [5] (however, see Sec. 4). We also checked that

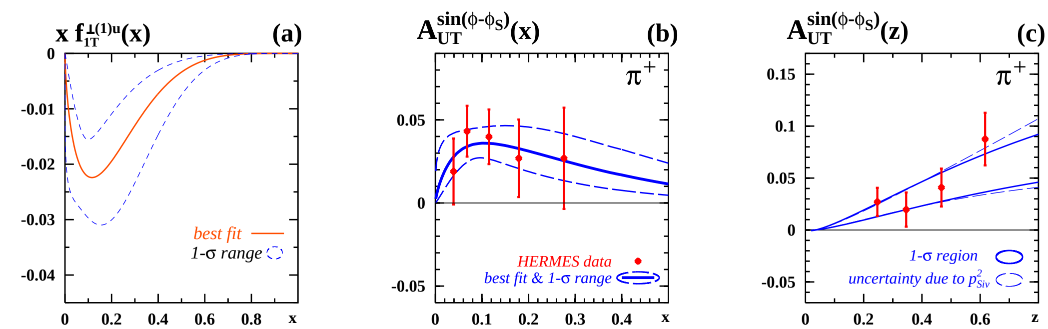

Figure 2: **a.** The u-quark Sivers function vs. x at a scale of $2.5\,{\rm GeV}^2$, as obtained from the HERMES data [5]. Shown are the best fit and its 1-σ uncertainty. **b.** and **c.** The azimuthal SSA $A_{UT}^{\sin(\phi_h-\phi_S)}$ as function of x and z for positive pions as obtained from the fit (4) in comparison to the data [5].

$1/N_c$-corrections are within the error bars of the data [5]. For that we assumed that the flavour singlet Sivers distribution is suppressed by exactly a factor of $1/N_c$ with respect to the flavour non-singlet combination according to Eq. (3). That is, with $N_c = 3$,

$$\left|(f_{1T}^{\perp(1)u} + f_{1T}^{\perp(1)d})(x)\right| \stackrel{!}{=} \pm \frac{1}{N_c}(f_{1T}^{\perp(1)u} - f_{1T}^{\perp(1)d})(x)\,, \tag{5}$$

where we use $f_{1T}^{\perp(1)q}(x)$ from (4) on the right-hand-side.

On an isoscalar target, such as deuteron, the entire effect is due to $1/N_c$-corrections. Assuming that charged hadrons at COMPASS are mainly pions, the rough estimate (5) of $1/N_c$-corrections yields results compatible with the COMPASS data [6], see Fig. 3.

Thus, the large-N_c approach works, because the precision of the first data [5, 6] is comparable to the theoretical accuracy of the large-N_c relation (3). Our results are in agreement with other studies [19, 20, 22].

We conclude that the HERMES and COMPASS data [5, 6] are compatible with the large-N_c prediction (3) for the Sivers function [32]. Remarkably, the sign of the extracted Sivers function in Eq. (4) agrees with the physical picture discussed in [33].

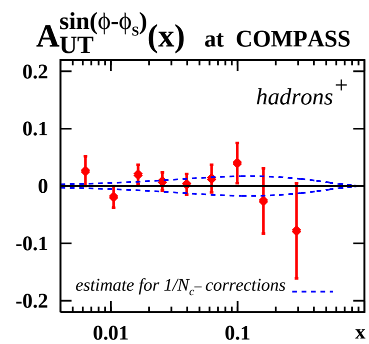

Figure 3: The Sivers SSA for positive hadrons from deuteron. Data are from COMPASS [6]. The theoretical curves indicate the magnitude of the effect on the basis of the estimate (5).

2.2 Sivers effect in the Drell-Yan process. Universility is a particularly interesting aspect of the Sivers function. On the basis of time-reversal arguments it is predicted [14] that this (and other "T-odd") distribution(s) have opposite signs in SIDIS and DY

$$f_{1T}^{\perp}(x, \mathbf{p}_T^2)_{\rm SIDIS} = -f_{1T}^{\perp}(x, \mathbf{p}_T^2)_{\rm DY}\,. \tag{6}$$

The experimental check of Eq. (6) would provide a thorough test of our understanding of the Sivers effect within QCD. In particular, the experimental verification of (6) is a crucial prerequisite for testing the factorization approach to the description of processes containing p_T-dependent correlators [9].

On the basis of the first information of the Sivers effect in SIDIS [5, 6] it was shown that the Sivers effect leads to sizeable SSA in $p^\uparrow\pi^- \to l^+l^-X$, which could be studied at COMPASS, and in $p^\uparrow\bar{p} \to l^+l^-X$ or $p\bar{p}^\uparrow \to l^+l^-X$ in the planned PAX experiment at GSI [42] making the experimental check of Eq. (6) feasible and promising [18]. Both experiments are dominated by annihilations of valence quarks (from p) and valence antiquarks (from $\bar{p}$, π^-). This yields sizeable counting rates, and the processes are not sensitive to Sivers antiquarks, that are not constrained by the present data, see [18]-[21].

On a shorter term the Sivers effect in DY can be studied in $p^\uparrow p \to l^+l^-X$ at RHIC. In pp-collisions inevitably antiquark distributions are involved, and the counting rates are smaller. We have shown, however, that the Sivers SSA in DY can nevertheless be measured at RHIC with an accuracy sufficient to unambiguously test Eq. (6) [25].

The theoretical understanding of SSA in $p^\uparrow p \to \pi X$, which originally motivated the introduction of the Sivers effect, is more involved compared to SIDIS or DY. No factorization proof is formulated for this process. The SSA can also be generated by twist-3 effects [34] that, however, could be manifestations of the same effect in different k_T regions [35].

3 Transversity and Collins effect

The transversity distribution function $h_1^a(x)$ enters the expression for the Collins SSA in SIDIS together with the equally unknown Collins fragmentation function [16] (FF) $H_1^a(z)$[1]

$$A_{UT}^{\sin(\phi+\phi_S)} = 2\frac{\sum_a e_a^2 x h_1^a(x) B_{\rm G} H_1^a(z)}{\sum_a e_a^2\, x f_1^a(x)\, D_1^a(z)}\ . \tag{7}$$

However, $H_1^a(z)$ is accessible in $e^+e^- \to \bar{q}q \to 2$jets where the quark transverse spin correlation induces a specific azimuthal correlation of two hadrons in opposite jets [11]

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\rm unp}\underbrace{\left[1+\cos(2\phi_1)\frac{\sin^2\theta}{1+\cos^2\theta}\,C_{\rm G}\times\frac{\sum_a e_a^2 H_1^a H_1^{\bar a}}{\sum_a e_a^2 D_1^a D_1^{\bar a}}\right]}_{\equiv A_1} \tag{8}$$

where ϕ_1 is azimuthal angle of hadron 1 around z-axis along hadron 2, and θ is electron polar angle. Also here we assume the Gauss model and $C_{\rm G}(z_1,z_2) = \frac{16}{\pi} z_1 z_2/(z_1^2+z_2^2)$.

First experimental indications for the Collins effect were obtained from studies of preliminary SMC data on SIDIS [36] and DELPHI data on charged hadron production in e^+e^- annihilations at the Z^0-pole [37]. More recently HERMES reported data on the Collins (SSA) in SIDIS from proton target [5, 7] giving the first unambiguous evidence that H_1^a and $h_1^a(x)$ are non-zero, while in the COMPASS experiment [6] the Collins effect from a deuteron target was found compatible with zero within error bars. Finally, year ago the BELLE collaboration presented data on sizeable azimuthal correlation in e^+e^- annihilations at a center of mass energy of 60 MeV below the Υ-resonance [8].

The question which arises is: *Are all these data from different SIDIS and e^+e^- experiments compatible, i.e. due to the same Collins effect?*

In order to answer this question we extract H_1^a from HERMES [7] and BELLE [8] data, and compare the ratios H_1^a/D_1^a from these and other experiments. Such "analyzing powers" might be expected to be weakly scale-dependent.

3.1 Collins effect in SIDIS. A simultanous extraction of $h_1^a(x)$ and $H_1^{\perp a}(z)$ from SIDIS data is presently not possible. We use therefore for $h_1^a(x)$ predictions from chiral quark-soliton model [38] which provides a good description of $f_1^a(x)$ and $g_1^a(x)$. The HERMES data on the Collins SSA [7] can be described in this approach if, at $\langle Q^2\rangle = 2.5\,\mathrm{GeV}^2$,

$$\frac{\langle 2B_{\rm G}H_1^{\rm fav}\rangle}{\langle D_1^{\rm fav}\rangle}\bigg|_{\rm HERMES} = (7.2\pm1.7)\%\ ,\quad \frac{\langle 2B_{\rm G}H_1^{\rm unf}\rangle}{\langle D_1^{\rm unf}\rangle}\bigg|_{\rm HERMES} = -(14.2\pm2.7)\%\ . \tag{9}$$

where "fav" ("unf") means favored $u\to\pi^+$ etc. (unfavored $u\to\pi^-$, etc.) fragmentation, and $\langle\ldots\rangle$ denotes average over z within the HERMES cuts $0.2\le z\le 0.7$.

The absolute numbers for $\langle 2B_{\rm G}H_1^{\rm fav}\rangle$ and $\langle 2B_{\rm G}H_1^{\rm unf}\rangle$ are of similar magnitude. This can be understood in the string fragmentation picture and the Schäfer-Teryaev sum rule [39]. Fit (9) describes the HERMES proton target data [7] on the Collins SSA (Figs. 4a, b) and is in agreement with COMPASS deuteron data [6] (Figs. 4c, d).

[1] We assume a factorized Gaussian dependence on parton and hadron transverse momenta [10] with $B_{\rm G}(z) = (1+z^2\ \langle\mathbf{p}_{h_1}^2\rangle/\langle\mathbf{K}_{H_1}^2\rangle)^{-1/2}$ and define $H_1^a(z) \equiv H_1^{\perp(1/2)a}(z) = \int \mathrm{d}^2\mathbf{K}_T \frac{|\mathbf{K}_T|}{2zm_\pi} H_1^{\perp a}(z,\mathbf{K}_T)$. The Gaussian widths are assumed flavor and x- or z-independent. We neglect throughout the soft factors [9].

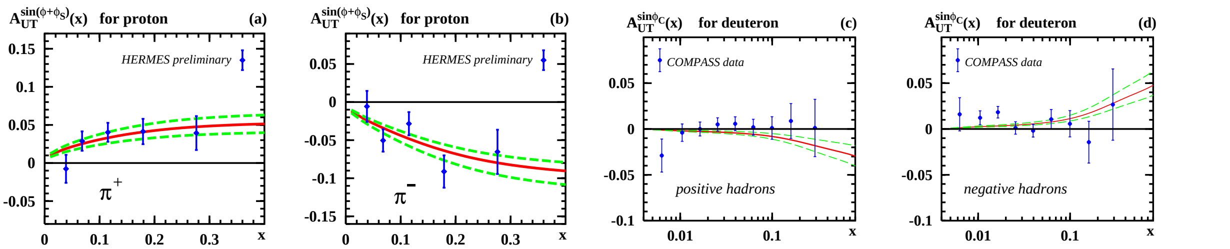

Figure 4: Collins SSA $A_{UT}^{\sin(\phi+\phi_S)}$ as function of x vs. HERMES [7] and new COMPASS [6] data.

3.2 Collins effect in e$^+$e$^-$. The $\cos 2\phi$ dependence of the cross section (8) could arise also from hard gluon radiation or detector acceptance effects. These effects, being flavor independent, cancel out from the double ratio of A_1^U, where both hadrons $h_1 h_2$ are pions of unlike sign, to A_1^L, where $h_1 h_2$ are pions of like sign, i.e.

$$\frac{A_1^U}{A_1^L} \approx 1 + \cos(2\phi_1) P_{U/L}(z_1, z_2) \, . \tag{10}$$

The BELLE data [8] can be described with the following Ansatz and best fit, which is shown in Fig. 5,

$$H_1^a(z) = C_a \, z \, D_1^a(z), \;\; C_{\rm fav} = 0.15, \;\; C_{\rm unf} = -0.45. \tag{11}$$

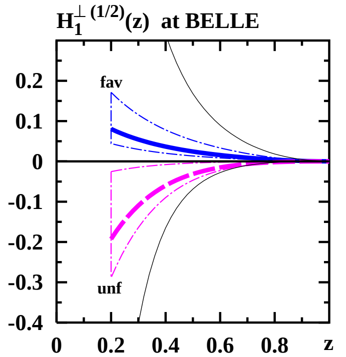

Figure 5: Collins FF $H_1^a(z)$ needed to explain the BELLE data [8]. The shown 1-σ error bands are correlated.

Other Ansätze gave less satisfactory fits. The azimuthal observables in e^+e^--annihilation are bilinear in H_1^a and therefore symmetric with respect to the exchange of the signs of $H_1^{\rm fav}$ and $H_1^{\rm unf}$. The BELLE data [8] unambiguously indicate that $H_1^{\rm fav}$ and $H_1^{\rm unf}$ have opposite signs, but they cannot tell us which is positive and which is negative. The definite signs in (11) and Fig. 5 are dictated by SIDIS data [7] and model [38] with $h_1^u(x) > 0$. In Fig. 6 (top) the BELLE data [8] are compared to the theoretical result for $P_{U/L}(z_1, z_2)$.

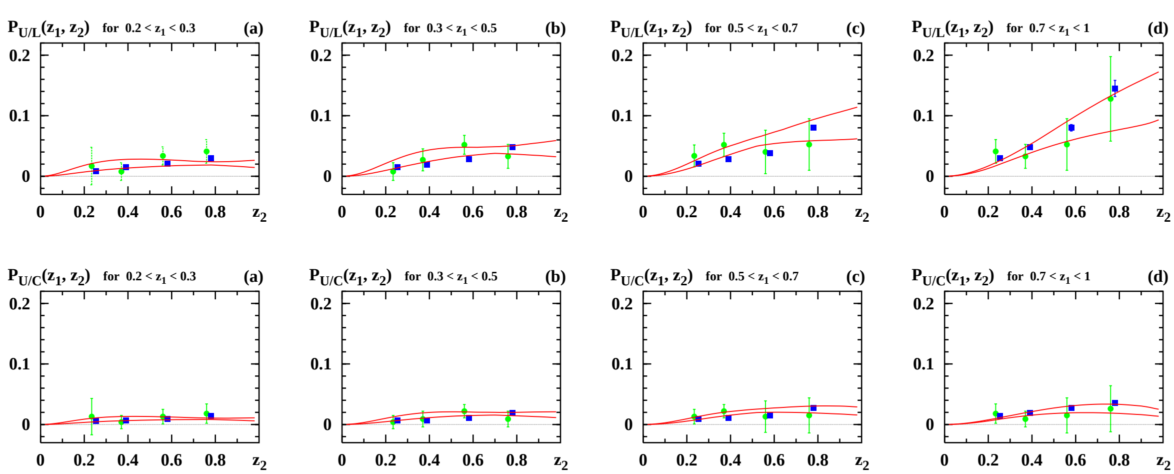

Figure 6: **Top**: $P_{U/L}(z_1, z_2)$ defined in Eq. (10) for fixed z_1-bins as function of z_2 vs. BELLE data [8]. **Bottom**: The observable $P_{U/L}(z_1, z_2)$ defined analogously, see text, vs. preliminary BELLE data [45]. Blue squares are new preliminary data, see Sec. 4.

3.3 BELLE vs. HERMES. In order to compare Collins effect in SIDIS at HERMES [5, 7] and in e^+e^--annihilation at BELLE [8] we consider the ratios H_1^a/D_1^a which might be less scale dependent. The BELLE fit in Fig. 5 yields in the HERMES z-range:

$$\frac{\langle 2H_1^{\rm fav}\rangle}{\langle D_1^{\rm fav}\rangle}\bigg|_{\rm BELLE} = (5.3\cdots 20.4)\%, \quad \frac{\langle 2H_1^{\rm unf}\rangle}{\langle D_1^{\rm unf}\rangle}\bigg|_{\rm BELLE} = -(3.7\ \cdots\ 41.4)\%\ . \tag{12}$$

The above numbers (errors are correlated!) and the result in Eq. (9) are compatible, if one takes into account the factor $B_{\rm G}<1$ in Eq. (9).

Assuming a weak scale-dependence also for

$$\frac{H_1^a(z)}{D_1^a(z)}\bigg|_{\rm BELLE} \approx \frac{H_1^a(z)}{D_1^a(z)}\bigg|_{\rm HERMES} \tag{13}$$

and considering the 1-σ uncertainty of the BELLE fit in Fig. 5 and the sensitivity to unknown Gaussian widths of $H_1^a(z)$ and $h_1^a(x)$, c.f. Footnote 1 and Ref. [23], one obtains also a satisfactory description of the z-dependence of the HERMES data [7] as shown in Fig. 7.

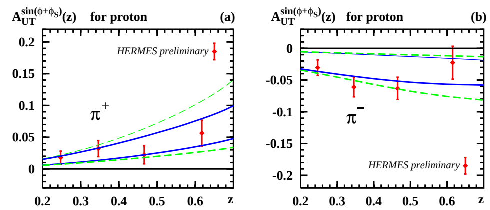

Figure 7: The Collins SSA $A_{UT}^{\sin(\phi+\phi_S)}(z)$ as function of z. The theoretical curves are based on the fit of $H_1^a(z)$ to the BELLE data under the assumption (13). The dashed lines indicate the sensitivity of the SSA to the Gaussian widths.

These observations allow to draw the conclusion that it is, in fact, the same Collins effect at work in SIDIS [5, 6, 7] and in e^+e^--annihilation [8, 45]. Estimates indicate that the early preliminary DELPHI result [37] is compatible with these findings [23].

3.3 Transversity in Drell-Yan process. The double-spin asymmetry observable in Drell-Yan (DY) lepton-pair production in proton-proton collisions is given in LO by

$$A_{TT}(x_F) = \frac{\sum_a e_a^2 h_1^a(x_1) h_1^{\bar a}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar a}(x_2)} \tag{14}$$

where $x_F = x_1 - x_2$ and $x_1x_2 = \frac{Q^2}{s}$. In the kinematics of RHIC A_{TT} is small and difficult to measure.

In the J-PARC experiment with $E_{\rm beam} = 50\,{\rm GeV}$ A_{TT} would reach $-5\,\%$ in the model [38], see Fig. 8, and could be measured [40]. The situation is similarly promising in proposed polarized beam U70-experiment [41].

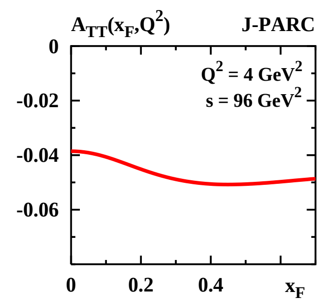

Figure 8: Double spin asymmetry A_{TT} in DY, Eq. (14), vs. x_F for the kinematics of J-PARC.

Finally, in the PAX-experiment proposed at GSI [42] in polarized $\bar pp$ collisions one may expect $A_{TT}\sim(30\cdots 50)\%$ [43]. There $A_{TT}\propto h_1^u(x_1)h_1^{\bar u}(x_2)$ to a good approximation, due to u-quark ($\bar u$-quark) dominance in the proton (anti-proton) [43].

4 New data and developements

Since our studies were completed [18, 21, 23] new data became available from SIDIS at HERMES [44] and e^+e^--annihilations at BELLE [45]. What is the impact of the new experimental results? Do they confirm our current understanding of the Sivers- and Collins-effects, or will they require a revision?

4.1 New results from BELLE. Interesting recent news are the preliminary BELLE data [45] for the ratio of azimuthal asymmetries of unlike sign pion pairs, A_1^U, to all charged pion pairs, A_1^C. The new observable $P_{U/C}$ is defined analogously to $P_{U/L}$ in Eq. (10) as $A_1^U/A_1^C \approx 1 + \cos(2\phi)\, P_{U/C}$. Fig. 6 (bottom) shows that the fit (11) from [23] ideally describes the new experimental points! Thus, the new data confirm the picture of the Collins function in Fig. 5, but will allow to reduce the uncertainty of the extraction.

4.2 π^0 Collins SSA. The (unpolarized or Collins) fragmentation functions for neutral pions are just the average of the favoured and unfavoured fragmentation functions into charged pions, due to isospin symmetry. Since in the HERMES kinematics the favoured and unfavoured Collins functions are of opposite sign and nearly equal in magnitude, $\langle 2B_{\rm G}H_1^{\rm fav}\rangle \approx -\langle 2B_{\rm G}H_1^{\rm unf}\rangle$ c.f. Sec. 3.1, one expects the π^0 Collins SSA to be nearly zero [23]. Most recent HERMES data confirm this prediction within error bars [44].

4.3 π^0 Sivers SSA. Isospin symmetry applies not only to fragmenation functions but to the entire effects. Thus, knowing the Sivers SSAs for charged pions one is able to predict the effect for π^0. In Figs. 9a, b we compare our predictions made on the basis of the results from [21] discussed in Sec. 2.1 with the most recent HERMES data [44]. The agreement is satisfactory. In particular, data on the z-dependence of the Sivers SSA provide a direct test of the Gauss model for transverse parton and hadron momenta [21]. As can be seen in Fig. 9b, within the present precision of data the Gauss Ansatz is useful.

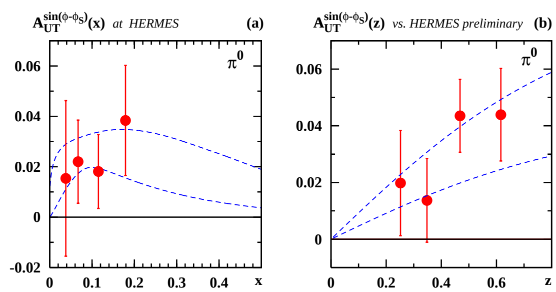

Figure 9: The Sivers SSA $A_{UT}^{\sin(\phi+\phi_S)}(z)$ for π^0 as functions of x and z. The preliminary HERMES data are from [44]. The theoretical curves are based on the extraction of the Sivers effect [21] from the HERMES data on $\pi^\pm$ SSAs [5].

4.4 Sivers effect for kaons. In the HERMES experiment also the Sivers effect for charged kaons was measured. For K^- the effect is compatible with zero within error bars. But for K^+ in the region of $x = (0.05 - 0.15)$ the SSA is about (2-3) times larger than the π^+ SSA [44], while for $x \geq 0.15$ the K^+ and π^+ SSAs are of comparable size within error bars. Can one understand this behaviour?

The "only difference" between the π^+ and K^+ SSAs is the exchange $\bar{d} \leftrightarrow \bar{s}$. Therefore, in our approach of Sec. 2.1, where we neglect the effects of Sivers strange and antiquarks one expects π^+ and K^+ SSAs of same magnitude. However, by including explicitly $\bar{u}$, $\bar{d}$, s and $\bar{s}$ Sivers distributions one could explain the observed enhancement of the K^+ Sivers SSA with respect to the π^+ SSA, provided the Sivers seaquark distributions would reach about 50% of the magnitude of the Sivers quark distributions. At small x this could be a reasonable scenario, see [26] for a detailed discussion. A simultaneous refitting of pion and kaon SSAs will give us a conclusive answer (see, however, the talk by Prokudin [24]).

5 Conclusions

Within the uncertainties of our study we find that the SIDIS data from HERMES [5, 7] and COMPASS [6] on the Sivers and Collins SSA from different targets are in agreement with each other and with BELLE data on azimuthal correlations in e^+e^--annihilations.

At the present stage of art large-N_c predictions for the flavour dependence of the Sivers function are compatible with data, and provide useful constraints for their analysis.

The favored and unfavored Collins FFs appear to be of comparable magnitude but have opposite signs, and $h_1^u(x)$ seems close to saturating the Soffer bound, other $h_1^a(x)$ are hardly constrained. This conclusion is supported by a simultanuous analysis of HERMES, COMPASS and BELLE data [24] with additional conclusion on the tendency of $h_1^d(x)$ to be negative. These findings are in agreement with old DELPHI and with the most recent BELLE data and with independent theoretical studies [20].

New HERMES and BELLE data confirm our first understanding of these effects, except for the HERMES data on the kaon Sivers SSA which may provide new interesting information on Sivers seaquarks. Further data from SIDIS (COMPASS, JLAB, HERMES) and e^+e^- colliders (BELLE) will help to improve this first picture.

The understanding of the novel functions $f_{1T}^{\perp a}$, h_1^a and H_1^a emerging from SIDIS and e^+e^--annihilations, however, will be completed only thanks to future data spin asymmetries in the Drell-Yan process. Experiments are in progress or planned at RHIC, J-PARC, COMPASS, U70 and PAX at GSI.

While the Sivers and Collins effects are the most prominent effects, it is important to keep in mind that there are further equally fascinating effects to be explored [46, 47, 48]. Preliminary COMPASS results on compatible with zero deuteron target SSAs beyond the Sivers and Collins effects were presented in [49].

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